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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Comparison of two ICT solutions: desktop PC versus thin client computing

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Abstract

Purpose Information communication technology (ICT) offers the chance of enhancing the efficiency of public services and economic processes. The use of server-based computing is supposed to reduce the energy and material consumption in ICT services. This hypothesis will be investigated and quantified looking at the whole life cycle of the products. In this paper, server-based computing in combination with thin clients (SBCTC) is compared to a typical desktop PC (DPC) workplace over a time period of 5 years.

Materials and methods The LCA method used in this paper is focused on the impact category of global warming potential. The calculations were performed using the Microsoft® Excel-based methodology for ecodesign of energy-related products tool. This tool includes the requirements of energy-related products (Directive 2009/125/EC). Moreover, an input-orientated method—material input per service unit (MIPS)—is applied which allows for an additional comparison between the two ICT solutions.

Results and discussion Electricity consumption could be identified as a crucial environmental impact factor of DPC and SBCTC with both methods. Depending on the user behavior, more than 200 kg CO_{2e} can be saved by switching from DPC to SBCTC. Over 80 kg CO_{2e} can be saved in the material and extraction life cycle stage. The largest savings are achieved in the material category electronics (about 70 kg CO_{2e}). A correlation analysis between the results of global warming potential (GWP) and the MIPS category "air" shows that both indicators GWP and air lead to the same conclusions when evaluating life cycle stages and ICT material categories.

Conclusions Taking into account all assumptions made in this paper, SBCTC saves more than 65 % of greenhouse gas emissions compared to DPC during the entire life cycle. To ensure further profound comparisons of the ICT solutions, current data on the energy demand and detailed information on the composition of the IT products should be made available by industry.

Keywords Environmental assessment · ICT · MEErP · MIPS · Thin client

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1 Introduction

Information communication technology (ICT) offers the chance of enhancing the efficiency of public services and economic processes. These enhancements should encompass green IT including ecodesign and resource efficient production (Ruth 2009; Murugesan 2008). ICT can be useful to reduce the carbon footprint of companies, e.g., by avoiding business trips or by optimizing logistics. On the other hand, more ICT involves higher electricity and resource consumption compared to the present situation.

Gartner states that the ICT sector is responsible for approximately 2 % of the global amount of CO_2 emissions considering the production, use, and disposal of ICT

equipment. This corresponds to the CO_2 emissions of all international flights (Gartner 2007). The ICT sector's own emissions are expected to increase in a business as usual (BAU) scenario, from 0.53 billion tonnes (Gt) carbon dioxide equivalent (CO_{2e}) in 2002 to 1.43 Gt CO_{2e} in 2020 (The Climate Group 2008). Instead of damaging the environment, specific ICT alternatives can have positive impacts, with the potential to reduce 15 % of CO_2 emissions in the ICT sector compared with the BAU scenario in 2020 (The Climate Group 2008).

The use of server-based computing is supposed to reduce the energy and material consumption in the provision of ICT services. This hypothesis was investigated and quantified looking at the whole life cycle of the products. Greenhouse gas emissions emitted during the entire life cycle of ICT equipment as well as material input (abiotic material, water, and air) were calculated and the results were incorporated in the analysis. In this paper, server-based computing in combination with thin clients (SBCTC) is compared to a typical desktop PC (DPC) workplace. The main difference between a DPC and SBCTC is that the thin client only visualizes the content which is calculated on an external server (Volchkov 2002).

The aim of the paper is to compare and evaluate these two ICT solutions using the "methodology for ecodesign of energy-related products" (MEErP) (global warming potential) and "material input per service unit" (MIPS). The corresponding results are presented and interpreted.

2 Materials and methods

The following chapters show the systems and the methods applied to compare the two different ICT solutions (DPC versus SBCTC). The functional unit and system boundaries, necessary assumptions, and allocation rules to permit the comparability of the systems are presented, and the applied methods MEErP and MIPS are described.

2.1 Functional unit and system boundaries

The two ICT systems to be compared are: thin client model IGEL UD3 in combination with a terminal server (software: Citrix XenApp 5.0/Windows Server 2003 R2, running virtualized on Citrix XenServer; hardware: IBM BladeCenter H and IBM HS22 blades with two quad-core processors of type Intel Xeon E5530 (2.4 GHz) and 48 GB of main memory) abbreviated as SBCTC and a standard office DPC as described in the "Lot 3 Personal Computers" study (cf. table 59 in IVF 2007, p. 122). The material composition of the thin client IGEL UD3 is taken from the study "Thin Clients 2011—Ecological and economical aspects of virtual desktops" (Fraunhofer 2011). The material compositions of both IT products are described in Table 2. Further IT operation concepts like desktop virtualization are not covered in this paper; instead they are addressed in the aforementioned study (Fraunhofer 2011).

The system boundaries of the two ICT solutions to be compared were chosen in compliance with the MEErP study (EU 2011). The life cycle analysis includes the whole life cycle (material extraction and production, manufacturing, distribution, use, and end of life stage) for both ICT solutions, DPC and SBCTC as depicted in Fig. 1. In contrast to the production stage, manufacturing comprises scrap losses during the production of metal and plastic components (EU 2011). A clear distinction between material extraction and production as recommended by Andrae (2011) was not possible as MEErP does not provide these life cycle stages. Benefits regarding reuse, recycling, recovery, incineration, and landfilling (EU 2011) were taken into account in the end of life stage.

For the calculation of the MIPS, the recycling stage is not calculated separately since most of the benefits resulting from the end-of-life stage are already enclosed in the material intensity (MI) values used. In the case of missing MI values of ICT components, the composition is estimated by the description given by the MEErP report (EU 2011). For example, a "Cu/Ni/Cr plating" approximately consists of 35 % Cu, 6 % Ni, and 59 % Cr. These shares are used for the calculation.

The authors used the present German energy mix (reference year 2010) for the comparison and a time frame of 5 years for the use of both ICT systems. According to a pilot study conducted by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU 2012), the carbon intensity of the German end energy mix will decrease by 18 % between 2010 and 2015 and even by 43 % between 2010 and 2020 which results in a smaller carbon footprint of the use stage. Nevertheless, changes in the carbon intensity of the German electricity supply are

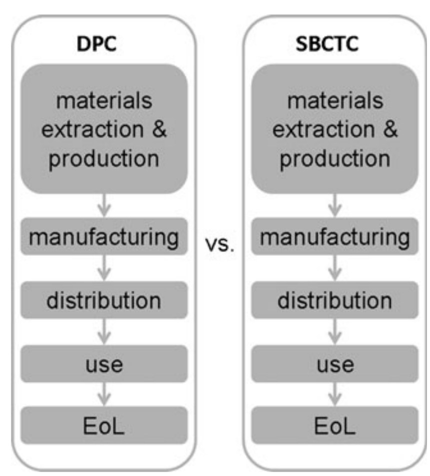

Fig. 1 Life cycle stages of the two ICT solutions DPC and SBCTC

highly uncertain since they strongly depend on political decisions. All materials are calculated with pre-chains up to the source (such as raw oil extraction for plastics or ore mining for iron production). The functional unit is defined as the supply of a computer workstation with two or three applications simultaneously for a time period of 5 years with 220 working days per year using SBCTC or DPC, respectively. Each working day comprises nine working hours. The applications not only include browsers and client/server applications, but also tools such as Microsoft® Office. It is assumed that both ICT solutions provide the same benefits for the user and are directly comparable.

2.2 Allocation and assumption

As the thin client needs a terminal server in the datacenter, a share of the impact of the terminal server (energy demand, resources to build it) has to be allocated to the thin client. One blade running virtualized terminal servers can supply 130 users. The average annual consumption of one blade on working days was measured to be 149.1 and 144.7 W on nonworking days (weekends and public holidays). A further 10 % is added to these values to compensate the imprecision of the BladeCenter's management module, which was utilized to monitor the energy consumption of each blade server (Fraunhofer 2011). The server needs additional cooling which has been included in the electricity demand with the help of power usage effectiveness multiplying the demand with factor 1.7. With 220 workdays, the annual electricity consumption is computed to be 2,413.8 kWh per year. The detailed material composition of the thin client was provided by the producer. Due to missing data, the composition of the server was estimated based on the following assumptions: Terminal server and PC systems have a similar material composition so that they can be compared on the basis of their weight. The weight of the server is about 4.5 kg compared to 12.75 kg, and therefore, the impact of the server material corresponds to 0.35 times the impact of a standard PC material (Fraunhofer 2011).

The typical DPC system for the comparison was selected from the production year 2007. The data source for the DPC material composition is the Lot 3 Personal Computers study (IVF 2007).

The electricity demand of the ICT equipment during the use stage was measured by Fraunhofer UMSICHT itself (Fraunhofer 2011) and is depicted in Table 1.

It is assumed that the thin client and DPC are used for nine working hours 220 days per year. The thin client is switched at night. In contrast, it is assumed that only 30 % of DPC users switch off the DPC overnight (scenario 1). According to estimates of the British environmental organization Global Action Plan, 30 % of all business computers in Great Britain are regularly not shut down (Global Action Plan 2007). In a

Table 1 Summary of the system boundaries and assumptions of DPC and SBCTC

Product and technology, nation, reference, system boundary	Lifetime (years)	Operating hours per year	Energy consumption in "idle mode" and "soft-off" mode	Electricity usage in use stage (kWh) within 5 years	Weight (kg)
Thin client UD3, Germany, Fraunhofer (2011), cradle-to-grave	5	Idle mode 220×9=1,980 h/year, soft-off 6,780 h/year	11.5 W, 1.9 W	178.26 kWh	2.69
Terminal server (IBM HS22), Europe, IVF (2007), cradle-to-grave	5	Idle mode 220×9=1,980 h/year, soft-off 6,780 h/year	149.1 W, 144.7 W Server is not switched off	2,413.8 kWh/130 user* 5 years=92.84 kWh	4.5 4.5/130=0.034 server share per thin client
Desktop PC, Europe, IVF (2007), cradle-to-grave	5	Idle mode, scenario 1, 2/3×220×9+1/3×220×24=3,080 h/year Scenario 2, 2/3×220×9+1/3×365×24=4,240 h/year	33.4 W, 0 W[a]	Scenario 1, 513.92 kWh Scenario 2, 707.63 kWh	12.75

[a] In order to achieve 0 W in the soft-off mode, the network card's wake-on-LAN functionality must be deactivated. Therefore, automated installation of applications and updates is not possible in this operating model

second scenario, about 30 % of PC users do not switch off their DPC even on nonworking days. For the USA, the environmental agency EPA assumes that almost 60 % of desktop computers are not turned off at night (Lüke 2007).

Other electricity consumption values for the use stage reported in literature are 600 kWh for 6 years (IVF 2007) or 860 kWh for 4 years, respectively (Ecoinvent 2008). These values fit well into the range of the consumptions used in this paper. The contribution of the life cycle stages and materials (material categories) on GWP and MIPS was identified analyzing the relative contribution to the overall impact.

2.3 Applied method to detect impacts of ICT use: MEErP method

The Microsoft® Excel-based MEErP tool to assess environmental impacts of energy using products was developed by Van Holsteijn en Kemma BV on behalf of the European Commission (DG Enterprise) in 2011. The tool takes into account the requirements of energy-related products (Directive 2009/125/EC) such as computers. The underlying methodology is based on a life cycle approach and also includes—apart from inventory data and technical parameters for energy-related products—specific impact assessment factors (Joint Research Centre 2010). The methodology looks at the primary energy consumption (total gross energy requirement in megajoules primary energy, electricity in megajoules, and primary energy and heating energy of fossil fuels in net calorific value), water utilization (process and cooling water), and waste (hazardous and nonhazardous waste). Furthermore, emissions into the air are included in the impact categories of global warming potential for a time horizon of 100 years [GWP100] (in CO_2 equivalent), acidification, acidification potential (in gram SO_2 equivalent), persistent organic pollutants (total concentration equivalent (Teq) of tetrachlorodibenzodioxin in nanogram I-Teq per product), non-methane volatile organic compounds (in grams), and heavy metals (in milligram Ni equivalent). Apart from these air emissions, polycyclic aromatic hydrocarbons (in milligram Ni equivalent) are included. Furthermore, emissions into water such as the eutrophication potential (in milligram PO_4 equivalent) and the release of heavy metals into water (in milligram Hg/20 equivalent) are considered in the MEErP method. This paper refers to the LCIA indicator global warming potential (GWP-100) using the characterization factors reported in the IPCC Fourth Assessment report on climate change of 2007 (IPCC 2007).

All results (emissions) are automatically calculated with the help of Excel® spreadsheets. The user has to enter the bill of materials (BOM) and the packaging volume of the product and is allowed to modify some parameters (e.g., recycling rates). The packaging volume of the product, for instance, is used for the estimation of the impacts of the distribution stage.

The materials in the BOM are differentiated into material categories (such as bulk plastics, ferrous metals, or electronics) and the material used (such as LDPE, stainless 18/8 coil, and slots/external ports). Insecurities of data and intercorrelations (insecurities in the ecological impact of materials) are not fully considered in the MEErP methodology. However, methodologies to incorporate uncertainty analyses have already been suggested by Andrae and Andersen (2011, 2010), Andrae et al. (2004), and Weber (2012).

Apart from the MEErP method, a material intensity analysis according to the MIPS concept was carried out. The MIPS methodology developed by Schmidt-Bleek (1994) looks at the use of all kinds of natural resources and not at the emissions of a product or process.

2.4 Method applied to evaluate environmental impacts—MIPS method

The MIPS method was selected as a second environmental impact assessment method. MIPS is an acronym for material input per service unit and may be calculated for all products or processes that provide a service (Schmidt-Bleek et al. 1998). The application of the two approaches (MEErP and MIPS method) allows the authors to detect differences and similarities in the results of the two assessment methods.

The MIPS method was developed at the German Wuppertal Institute for Climate, Environment and Energy and is a useful tool for measuring human-induced material flows (Sinivuori and Saari 2006). In contrast to other life cycle assessment (LCA) methods, no emissions are calculated; instead natural resources consumed by a product during its entire life cycle are estimated. The five input categories: "abiotic materials," "biotic materials," "water," "air," and "earth movements in agriculture and forestry" are assessed by the MIPS methodology. Abiotic materials include mineral raw materials from mines, quarries and smelting plants, fossil fuels, rock, and earth that are moved during the quarrying or excavation of abiotic raw materials and unused extracted earth from for example the construction and maintenance of buildings and transport infrastructure (Schmidt-Bleek 1998a). Biotic materials encompass biomass of plants from human cultivation or biomass derived from uncultivated land but for human use, e.g., wild animals, fish, and wild plants. Water use refers to water which is actively extracted from nature comprising also water extracted by technical means and water flowing through a water wheel located in a natural channel. The consumption of air represents the amount of air which is needed for combustion and the air used in other chemical and physical reactions (Schmidt-Bleek 1998a). The calculation is based on the weight of the air component, which is transformed, e.g., oxygen which is needed for combustion. The

category earth movements in agriculture and forestry involves erosion and mechanical tillage of the soil, such as ploughing and harrowing. This paper concentrates on the material inputs abiotic material, air, and water. Insecurities of data and inter-correlations (insecurities in the ecological impact of material flows) are not considered in the MIPS methodology.

2.5 Calculation of MIPS for the entire life cycle of both ICT solutions

To calculate the material input per ICT solution, material and energy demands over the entire life cycle are needed, as illustrated in Fig. 2 (step 1). In step 2, the corresponding MIs are selected on the basis of a list provided by the Wuppertal Institute for Climate, Environment and Energy. The material and energy demand in kilograms of material or kilowatt-hour energy is multiplied with the corresponding MI values to calculate the material intensity (MIT) (step 3). A closer description of the calculation is given by Ritthoff et al. (2003). In case there should be no MI value available for an ICT component, the composition is estimated according to MEErP or further literature. In the manufacturing stage, the energy demand of the processes as well as the process materials and transportation are taken into account. In the use stage, the energy demand of the ICT solutions in kilowatt-hour serves for calculating (see Table 1). In the distribution stage, the energy demand for heating a store, the packaging of the ICT product, as well as the transportation of the ICT product is considered. Finally, all material intensities are summed up to obtain the MIPS values of the ICT solution in each category such as abiotic material (step 4).

2.6 Inventory data

In cooperation with the producer of the thin client IGEL UD3, in total, 73 ICT components could be identified (mass 2.69 kg) (Fraunhofer 2011). These ICT components were assigned to the material categories and materials suggested by the MEErP methodology and are summarized in Table 2. In addition, the BOM of the analyzed desktop PC is depicted on the right hand side of the table. This inventory data are used in a later stage for calculating the GWP and MIPS of both ICT solutions.

The primary energy consumption of the thin client in the manufacturing stage was calculated using the MEErP Microsoft® Excel tool and amounts to 109.5 MJ. A closer description of the energy included for the manufacturing of the ICT components is given in the MEErP Methodology Report Part 2: Environmental Policies & Data (EU 2011). The primary energy calculated for the manufacturing stage of the desktop PC is 352.91 MJ, about three times higher than the energy needed for the thin client. A summary of the energy requirements in the use stage is given in Table 1. The material and energy demand in the end of life stage is estimated via the MEErP tool. The standard values for reuse, recycling, recovery, incineration, and landfilling given in the MEErP report part 1 page 123 are used in this paper (EU 2011).

3 Results

Figures 3–8 present the results of the comparison of SBCTC and DPC solutions. Figure 3 shows the GWP in the life cycle

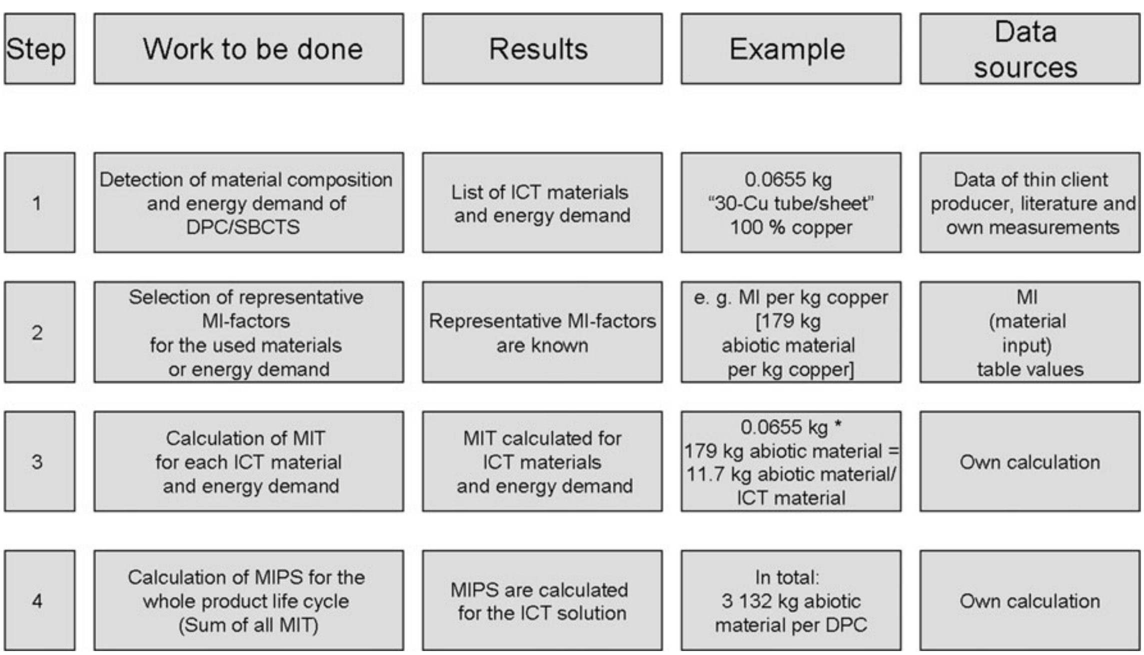

Fig. 2 Calculation of MIPS "abiotic material" for an ICT solution

Table 2 Bill of materials of a thin client IGEL UD3 and a desktop PC

Thin client IGEL UD3			Desktop PC (IVF 2007)		
Material	Material category	Mass [g]	Material	Material category	Mass [g]
1, LDPE	Bulk plastics	11.90	1, LDPE	Bulk plastics	246.00
11, ABS	Bulk plastics	345.74	11, ABS	Bulk plastics	380.75
13, PC	Technical plastics	1.16	12, PA 6	Technical plastics	137.68
17, flex PUR	Technical plastics	2.00	13, PC	Technical plastics	264.25
22, St sheet galv.	Ferrous metals	785.16	15, Epoxy	Technical plastics	97.90
25, ferrite	Ferrous metals	8.30	17, Flex PUR	Technical plastics	1.50
26, stainless 18/8 coil	Ferrous metals	120.70	22, St sheet galv.	Ferrous metals	6,312.30
29, Cu winding wire	Non-ferrous metals	180.60	23, St tube/profile	Ferrous metals	106.50
41, Cu/Ni/Cr plating	Coating	45.30	24, Cast iron	Ferrous metals	482.50
45, big caps and coils	Electronics	347.02	25, Ferrite	Ferrous metals	0.00
46, slots/extension ports	Electronics	96.75	26, Stainless 18/8 coil	Ferrous metals	9.50
47, IC's avg., 5 % Si, Au	Electronics	16.40	27, Al sheet/extrusion	Non-ferrous metals	314.53
48, IC's avg., 1 % Si	Electronics	7.07	28, Al diecast	Non-ferrous metals	15.00
49, SMD/LED's avg.	Electronics	10.26	28, Cu winding wire	Non-ferrous metals	257.00
50, PWB 1/2 lay 3.75 kg/m^2	Electronics	4.89	29, Cu wire	Non-ferrous metals	333.50
52, PWB 6 lay 2 kg/m^2	Electronics	115.70	30, Cu tube/sheet	Non-ferrous metals	66.50
53, solder $SnAg_4Cu_{0.5}$	Electronics	12.77	40, powder coating	Coating	1.62
57, cardboard	Miscellaneous	546.00	45, big caps and coils	Electronics	482.50
58, office paper	Miscellaneous	0.13	46, slots/extension ports	Electronics	310.00
98, controller board	Electronics	32.17	47, IC's avg., 5 % Si, Au	Electronics	69.00
			48, IC's avg., 1 % Si	Electronics	95.50
			49, SMD/LED's avg.	Electronics	193.50
			50, PWB 1/2 lay 3.75 kg/m^2	Electronics	78.00
			52, PWB 6 lay 4.5 kg/m^2	Electronics	162.50
			53, solder $SnAg_4Cu_{0.5}$	Electronics	48.00
			57, cardboard	Miscellaneous	2,286.5
Sum		2,690.02	Sum		12,752.53

stages of materials extraction and production, manufacturing, distribution, utilization, and end of life. The calculations of the GWP of a DPC in its entire life cycle result in 412 kg CO_{2e} (scenario 1) and 528 kg CO_{2e} (scenario 2). This is more than two times higher than the GWP of SBCTC amounting to 141 kg CO_{2e}. Most of the greenhouse gas emissions result

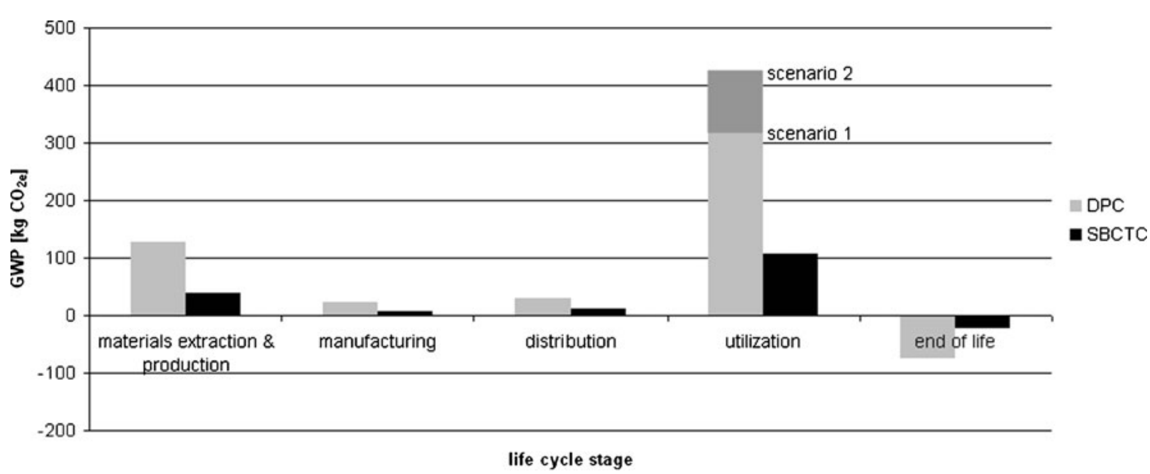

Fig. 3 Greenhouse gas emissions in the life cycle of DPC and SBCTC with a using time of 5 years

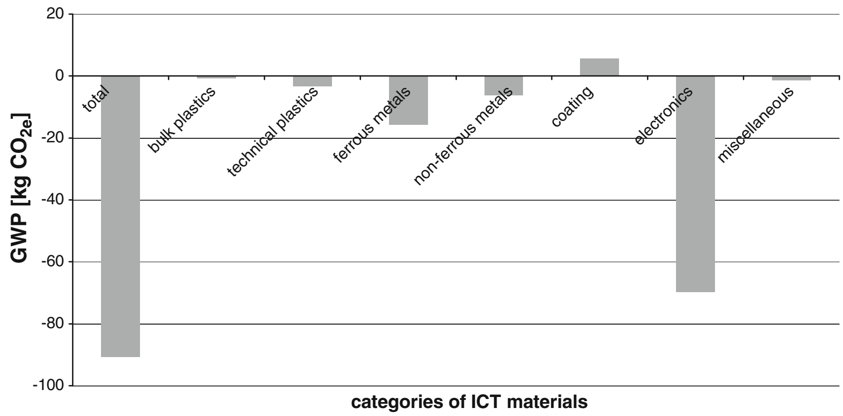

Fig. 4 GWP savings in the materials extraction and production stage of a SBCTC in comparison to DPC

from the use stage, which covers the demand of electricity. This stage shows the biggest differences in GWP: in total, the DPC causes greenhouse gas emissions that exceed those of a SBCTC solution by 201 kg CO_{2e} in scenario 1 and 317 kgCO_{2e} in scenario 2. The greenhouse gas emissions referring to the materials extraction and production stage also differ significantly between these two ICT solutions. While the DPC causes 128 kg CO_{2e}, the SBCTC results in greenhouse gas emissions of 38 kg CO_{2e}, which makes a difference of 90 kg CO_{2e}.

A closer look at the differences of DPC and SBCTC in the materials extraction and production stage reveals that the difference of 90 kg CO_{2e} mainly results from the amount and type of electronics used in the DPC. As illustrated in Fig. 4, approximately 70 kg CO_{2e} is reduced in the material category electronics including the ICT materials: 45, big caps and coils; 46, slots/external ports; 47, integrated circuits' (IC) avg., 5 % Si, Au; 48, IC's avg., 1 % Si; 49, SMD/LED's avg.; 50, printed wiring board (PWB) 1/2 lay 3.75 kg/m^2; 51, PWB 6 lay 4.5 kg/m^2; 52, PWB 6 lay 2 kg/m^2; 53, solder $SnAg_4Cu_{0.5}$; and 98, controller board. Further 15 kg CO_{2e} is saved in the material category "ferrous metals" including the ICT materials: 22, St sheet galvanized; 23, St tube/profile; 24, cast iron; 25, ferrite; and 26, stainless 18/8 coil. Moreover, greenhouse gas reductions are detected in the material categories "non-ferrous metals" (6 kg CO_{2e}), "technical plastics" (3 kg CO_{2e}), and bulk plastics (0.6 kg CO_{2e}). The amount of 6 kg CO_{2e} is emitted in the material category "coating" referring to the rear panel.

The greenhouse gases associated with the ICT materials from the materials extraction and production stage of a single thin client (IGEL UD3) are shown in Fig. 5. According to Fig. 5, the major part of the GWP is caused by the thin client materials "47, ICs avg., 5 % Si, Au" (integrated circuit based on Si wafer 200 diameter; ca. 20 %), "45 big caps and coils" (capacitors (Al) and coils (Cu and Fe) components on a PWB, approx. 12 %), 41 Cu/Ni/Cr plating (copper–nickel alloy on rear panel), and "98 controller board" (flash card reader, small outline dual in-line memory module SO-DIMM).

Similar results can be found for the DPC. The highest GHG emissions are caused by "47, IC's avg., 5 % Si, Au" (35 kg CO_{2e}). But also the 45 big caps and coils are responsible for 10 kg CO_{2e}. In contrast to the thin client, the GWPs of the materials used in a DPC are strongly influenced by "22, St sheet galvanized" and "49, SMD/LED's average."

The calculation of the whole life cycle material intensity using the MIPS methodology yields similar results. The

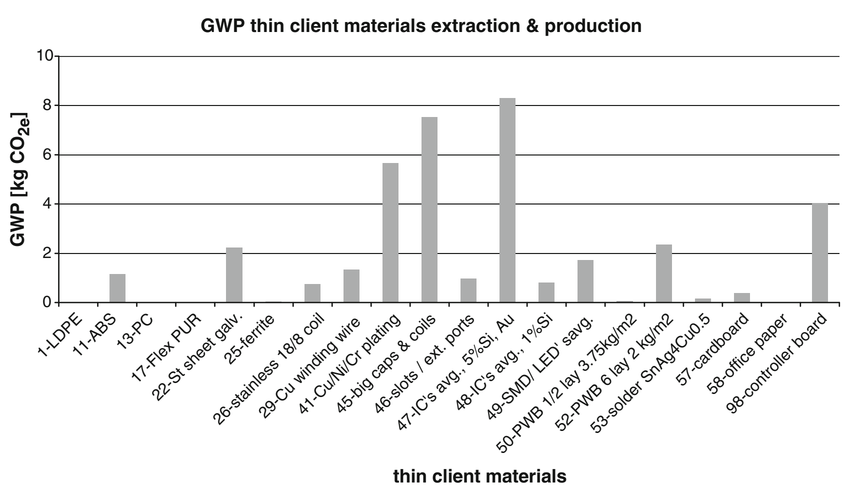

Fig. 5 GWP in the materials extraction and production stage of a thin client

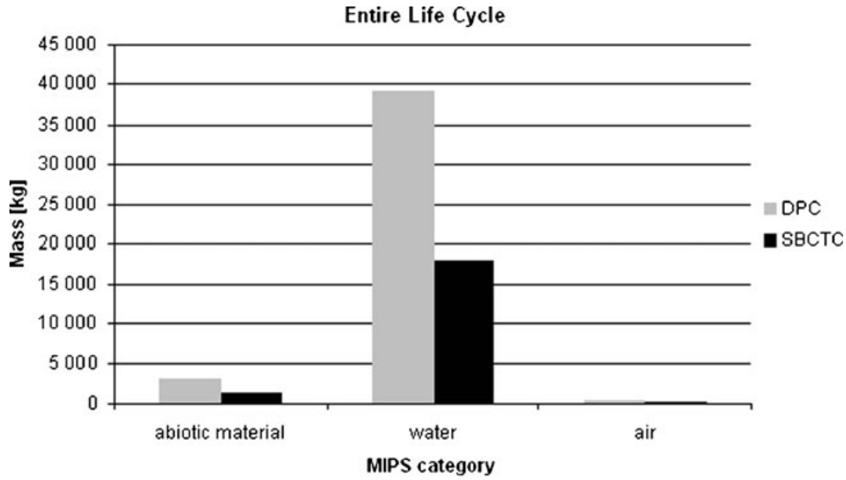

Fig. 6 Resources demand in the categories abiotic material, water, and air of a DPC and SBCTC

MIPS categories of "earth movements" and "consumption of biotic materials" are often missing in the MIT table (Wuppertal Institute for Climate, Environment and Energy 2003) and therefore have to be neglected. The use of resources in the categories of abiotic material, water, and air of a DPC is about two times higher than the use of resources of SBCTC also considering cooling for the terminal server (compare with Fig. 6). The demand of abiotic material in the life cycle of a DPC is about 3,132 kg in comparison to 1,285 kg with a SBCTC solution. The water demand in the life cycle of a DPC is more than two times higher than the demand of the SBCTC (39 t/18 t) and the use of air is also approx. two times higher (389 kg/191 kg).

In all MIPS categories, the highest resource requirement refers to the use stage, which means that the needed electricity mainly accounts for the resources demand (Fig. 7). Fifty-two percent of abiotic material (ca. 1,600 kg) for a DPC and 66 % (approx. 850 kg) for a SBCTC for instance refer to the use stage. Apart from the use stage, the materials extraction and production stage has a significant influence on the demand of "abiotic materials" (about 45 % of a DPC and about 31 % of a SBCTC). In the case of air, 67 % for a DPC and 72 % for a SBCTC refer to the use stage and only 19 % (DPC) and 11 % (SBCTC) are caused in the materials extraction and production stage.

Looking at the savings of air in the materials extraction and production stage when switching from a DPC to a SBCTC system, about 55 kg of air in total could be saved as depicted in Fig. 8. The highest savings (about 46 kg air) can be achieved in the material category "electronics." Only in the material category coating that additional air is required.

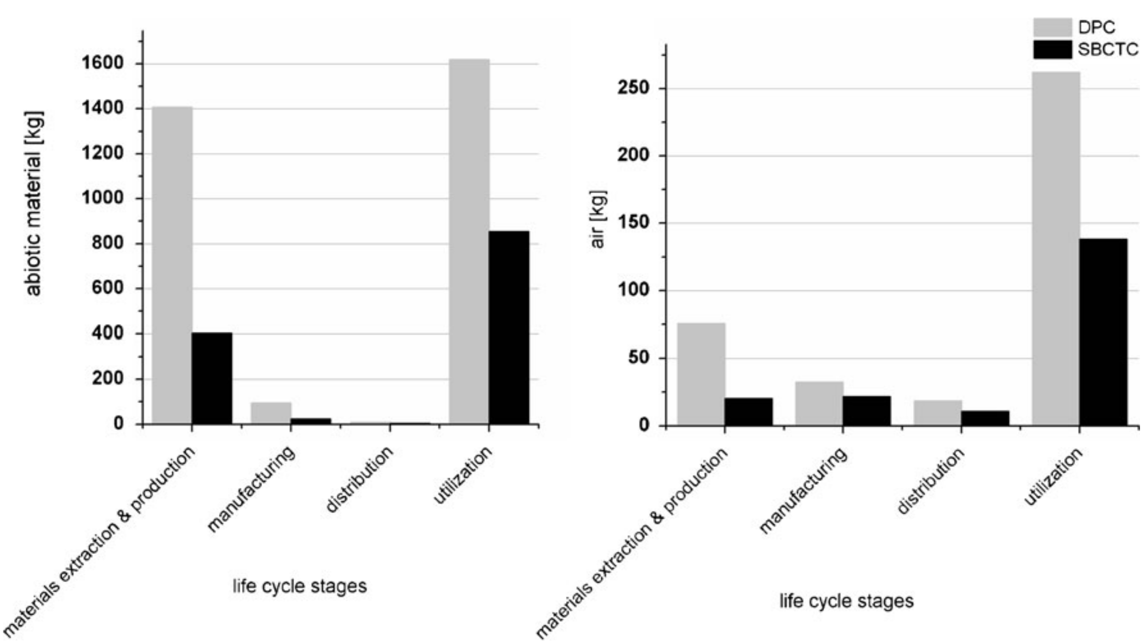

Fig. 7 Abiotic material and air in the life cycle stages of a DPC and SBCTC

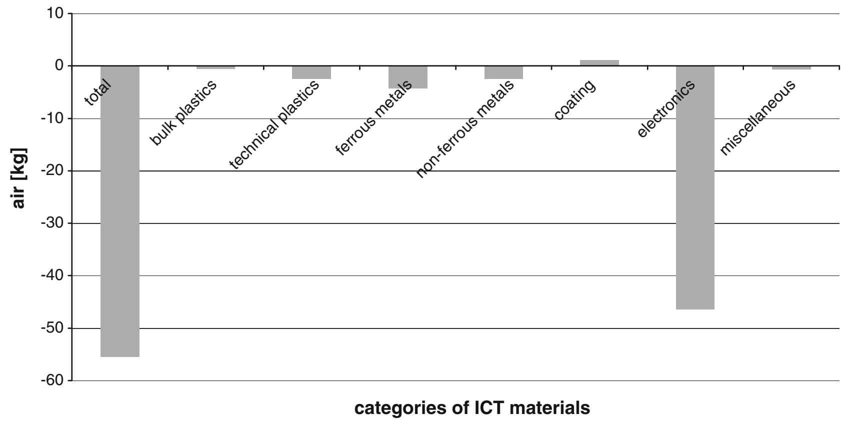

Fig. 8 Air savings in the materials extraction and production stage of a SBCTC in comparison to DPC

4 Discussion

4.1 Method discussion and assumptions

There are a number of premises leading to insecurities of results. The most important point is that the two ICT solutions provide the same benefit to the user. One difference is the CD drive in the DPC which offers a function not provided by the SBCTC solution. If a CD drive is needed, a separate drive has to be plugged in via USB interface. The authors assumed that the solutions are nevertheless comparable for most standard operations. It would make sense to create user scenarios to further investigate this impact. The SBCTC solution offers advantages regarding data security, reliability, costs at the relatively same working speed.

The data quality of the material composition, the energy demand of the thin client, the terminal server, and the DPC are very important. Today, the ICT branch is characterized by very short innovation cycles so that the data are already old when they are made available to the public. Another issue is the number of users which can be supplied by a terminal server. This number varies depending on user demands and server capacity. In this study, the energy demand for the cooling of the server is estimated cautiously. Nevertheless, in case of doubt, the authors used the worst case estimates because it is not possible to predict and quantify developments exactly.

Another premise which leads to insecurities is that both ICT products are calculated for a life time of 5 years. Although ICT products are often leased for 3 years only, a 5-year life time was used since IT devices are often reused by a second user. Furthermore, concrete data on terminal servers provided by the industry would improve the LCI data quality. The MIPS method has also insecurities as it does not offer necessary values on data uncertainties.

A consistent comparison of the results found in this study with other studies on desktop computers is nearly not possible since the scopes of other studies, e.g., analyzed in Andrae and Anderson (2010), differ strongly (e.g., screen is often included, outdated data). A study on a DellOptiPlex 780 Mini Tower indicates that this IT device has a carbon footprint of 720 kg CO_{2e} in Europe considering a use stage of 4 years (Stutz 2011). That value would be in the same range as determined in this paper. However, other LCA

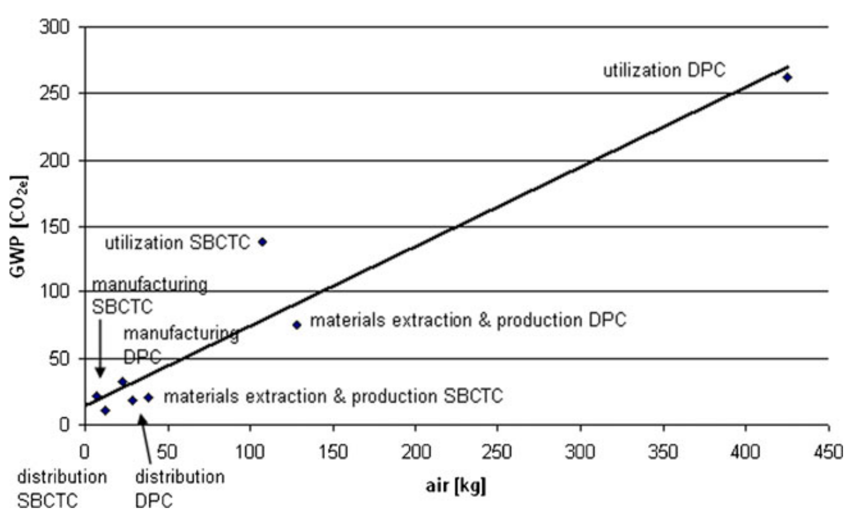

Fig. 9 Correlation between the air and GWP of a DPC and SBCTC

studies have calculated carbon footprints of PCs between 249 and 1,880 kg CO_{2e} (Teehan and Kandlikar 2012) showing high differences between different devices and data sources. Further LCA studies on SBCTC that could be used for drawing comparisons are not publicly available.

4.2 Correlation between results of the methods

Both indicators—GWP and MIPS—indicate that the electricity consumption in the use stage and the materials extraction and production stage are crucial for the environmental impact. A scatter plot of the air demand of SBCTC and DPCs and GWP for all life cycle stages is illustrated in Fig. 9. As shown in Fig. 9, the life cycle stages show a high correlation (R^2= 0.92). That means that both indicators lead to the same conclusions in evaluating life cycle stages.

A further correlation analysis between the GWP and the MIPS category air of all ICT material categories as introduced in Figs. 4 and 8 of a DPC and a SBCTC indicates a high correlation, too (R^2=0.98/0.96). This means that the GWP and the MIPS category air correspond well with each other in the case of weighting ICT material categories. However, a further comparison of GWP and the MIPS category air of individual ICT materials yields major differences.

5 Conclusions

The whole life cycle of DPC or SBCTC shows greenhouse gas emissions of 412 kg CO_{2e} (scenario 1, DPC) and 528 kg CO_{2e} (scenario 2, DPC) compared to 141 kg CO_{2e}, (SBCTC). In consideration of all assumptions made in this paper, SBCTC saves more than 270 kg CO_{2e} (i.e., 65 %) of greenhouse gas emissions compared to DPC during the entire life cycle.

The MIPS categories abiotic material, water, and air achieve savings of 1.8, 21, and 0.2 t for the SBCTC compared with the DPC solution. In the entire life cycle, the use of resources in the categories abiotic material, water, and air of a DPC is about two times higher than the use of resources of SBCTC.

Electricity consumption in the use stage could be identified as the crucial impact factor on GWP and the MIPS category air of DPC and SBCTC. The greenhouse gas emissions for DPC and SBCTC caused by the energy consumption in the use stage account for more than 70 % of the total greenhouse gas emissions in the entire life cycle.

The analysis of GWP caused by the ICT materials used in DPC and SBCTC has shown that ICT electronics installed in DPC such as surface-mounted devices, integrated circuits, and copper–nickel alloys result in a higher GWP of DPC compared to SBCTC in the materials extraction and production stage. Despite of lower material requirements of SBCTC compared with DPC, the installation of single materials with a high global warming potential such as the rear panel of the thin client results in high greenhouse gas emissions (see Fig. 4 for coating materials). Therefore, the energy consumption of both ICT solutions should be further reduced by technical optimizations (e.g., by developing more energy-efficient hardware and software) and changes in customer behavior (for instance, switch off of DPC at night). The implementation of a better ecodesign of ICT products as requested by the Directive 2009/125/EC on ecodesign of energy-related products and applied in the MEErP method is an important step towards resources and greenhouse gas savings.

A challenge for further research is the acquisition of detailed information on the composition of ICT equipment. To ensure a good comparison of future ICT solutions, up-to-date information on energy demand and material composition of ICT products should be made available by the industry.

The implementation and dissemination of existing labels such as “Energy Star” or “Blauer Engel” are one step ahead in order to inform the customers. Apart from these labels, the forthcoming LCA standardization of ICT equipment will have an enormous impact on legislation and customer information, e.g., about carbon footprint. A first LCA standard for ICT is currently being developed by ETSI (Andrae 2011; ETSI 2011).

Green IT will be of growing importance in the future due to an increased demand for hardware and software and scarce resources (e.g., of rare metals). New electrical and electronic products with a short life span on the market cause a growing amount of electronic waste (Hertwich and Roux 2011). This fact alone implies the demand for research on environmental benign production (following, e.g., design for environment) and better recycling technologies to redirect resources into the economic cycle. Moreover, emerging mobile solutions such as smart phones and pads may complement existing ICT solutions at work. However, as they will probably not replace existing ICT devices, they will lead to additional pressure on the environment.

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